3D Recycling: Printed Part to Usable Filament

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Introduction

One drawback of the increased use of 3D printers is waste of expensive material. In many cases 3D-printed parts are only used for visualization or verification of a design, which means these parts have no long-term usefulness. This is especially true in an educational setting where students are often tasked to make parts primarily as a learning experience. The cost of stocking 3D printer filament is higher than necessary due to the large amount of waste involved. The has authors have addressed this issue by designing a device that recycles printed parts back into usable filament.

Our Senior Capstone Design team has developed and tested a prototype to recycle a specific filament material called polylactic acid (PLA), which is currently the most commonly used material for educational 3D printers at Ohio Northern University. The prototype addresses the cycling process in a three-step sequence of reduction, extrusion, and spooling. The reduction phase uses a mechanical shredder that breaks the printed parts into small chips that can be fed into the extruder. The material from the shredder is then extruded into a filament of the required diameter for Makerbot® Replicators. Once extruded, the filament is wrapped onto a spool that is compatible for use in the 3D printer. This report will discuss the design process that led to the creation of the 3D Recycling prototype, and the performance evaluation observed during product testing.

Preliminary Research

Many design decisions were influenced by competitor research, while others were formed from industry or regulatory standards. Listed below are descriptions of some of the aspects that have affected the design of the system.

One competitor, the Protocycler[1], was identified as a direct competitor. The Protocycler has reduction, extrusion, and spooling processes incorporated in its design. This product is a great starting point for the capstone project because it creates a standard for the 3D Recycler. The standards set by this direct competitor include; extrusion rate (10ft/min), filament tolerance (1.75±.05mm), machine size (15"x14"x9"), safety standards, amount of user interaction to complete recycling, power consumption (90 W), and aesthetic appeal[1]. The weak points of Protocycler's product were identified as the price, spool neatness, and color separation, meaning there is no way of separating the filament colors if more than one color is being recycled.

From market research, it was identified that the majority of the competitor's products only provide the customer with a means of extruding filament that is already reduced into a long strand. Parallel products were identified as products which only contained the extrusion process. Some of these products also had reducing processes and spooling processes available for purchase as separate components but did not have all three processes combined into a single, purchasable unit. Obtaining information from competitors presented quantifiable data for comparison of the designed system against competitor data to ensure that the designed system matches or exceeds the state of the art systems. Some competitor systems are controlled by manual input to alter speeds and temperatures while some competitors use programming to control these values. The post-processing, or spooling process, is also similar between competitors. The spooling systems use a similar method of rotating the filament on a spool while maintaining tension as the filament is extruded.

3D printing filament specifications for filament already on the market provided insight in the determination of tolerancing, expected amount of filament needed to create a usable quantity of filament (both length of filament and mass of filament spool), and for cost analysis (how much will users expect to save by using this machine). Each spool used for the Makerbot Replicator 2, costs about $50[5]. From the specifications of filament on the market, the diameter constraint of 1.75mm +/- 0.05 mm was created[5]. The recommended heating temperature for extrusion is 180℃ to 220℃[1]. The goal is for the design to be capable of extruding 0.5kg of filament into a spool. This will create a half-full spool that is valuable for reuse.

Various standards were used to better define the product, specifically regarding safety regulations. It was found that limitations on hot surfaces and noise level are not regulated by OSHA, but recommendations do exist. It is considered safe to hold metal at temperatures no greater than 50℃[3]. Hearing damage can occur at noise levels above 85 decibels[4]. These recommendations were implemented into the project constraints in order to keep the design safe.

The following constraints and evaluation metrics were developed through competitor, client interests, and various safety parameters.

Constraints:
The system must…

- -Recycle PLA Filament
- -Extrude a diameter of 1.75mm +/- 0.05 mm
- -Enclose all surfaces over 50℃
- -Be safe to use indoors without ventilation
- -Fit through a standard 36" doorway
- -Run on a standard 110V AC wall plug-in
- -Not produce noise above 85 decibels

Recycling PLA filament is a requirement for the 3D Recycler product as that is the filament used in the Makerbot Replicator 2. The extruded filament diameter of 1.75mm is the size of filament that the 3D printers are capable of handling and currently use. The tolerance of +/- 0.05 mm was determined from filament manufacturers' specifications and other competitors' products[1]. It is important that the specified diameter is maintained in order to decrease the chance of the filament jamming while being used in 3D printers.

Safety measures and practicality were also addressed in the constraints. By ensuring that the product can fit through a 36” doorway will allow the product to be relocated without a major hassle. Also, the product must run on a standard wall outlet in so that it can be used in any room without having to make changes to that room. In order to keep the user and other people around the design safe, any surface over 50℃ must be enclosed because it is not safe to hold metal above this temperature[3]. To avoid hearing damage, the product must be designed such that it does not produce noises above 85 decibels[4].

Evaluation Metrics:
The evaluation metrics listed below were established as a means of quantifiably comparing the developed prototype to competitor products.

-Cost: less expensive is better
-Footprint: smaller is better
-3D Printed Part Size Capacity: larger is better
-Ability to reduce printed parts at various infills: higher infill percentage is better
-User Interactions Required: less is better
-Unusable PLA Filament: less is better
-Material Compatibility: more variety is better
-Weight: lighter is better

A product that is cost effective is beneficial to the customer and provides a faster return on investment. Also, a product that only uses a small area will allow for more space to be used in a room for other things. A lightweight product is more desirable so that the customer can easily move it if necessary. Less work required by the user when reducing, extruding, and spooling the PLA filament is desired. The product should have to do most of the work, not the user.

A product that can handle large parts with a high infill percentage and not waste filament during the recycling process is desired in order to maximize the amount of used filament that can be recycled. Although the product only is required to recycle PLA filament, having the capability to recycle other plastics could be useful as 3D printing evolves.

Potential Solutions

Multiple solutions to the reducing, extruding, and spooling processes were proposed. All designs were made to meet the established constraints. Using evaluation metrics and information obtained from preliminary testing, the potential solutions were narrowed down to one, which is explained in the Proposed Solution section.

Reduction Process:
The melting design is a concept that utilizes a heated area that reduces the entire 3D printed part to a liquid state at which point it would be redirected into a storage containment to be used in a plunging extrusion design. A downside to this design was the potential for toxic fumes released from PLA filament at temperatures above 220℃, as was observed in preliminary testing. Also, a user would need to interact with the part significantly more, and the danger for the user to get burned is high with reduction by melting.

An impact to a PLA filament is one way that parallel competitors recommend to reduce filament into an extrudable size. This method was tested using a hammer and a hydraulic press. The results of this test indicated that, while it is possible to reduce 100% infill with impacts or compression, the amount of force required to reduce solid printed parts would not be feasible for our machine, specifically due to size and usability.

The direct competitor, Protocycler, shreds 3D-printed parts for use in their extruding process. Shredding can be an effective way to reduce the parts to a desired size rather quickly. Safety, cost, and user interaction are concerns with shredding. Paper shredders can be used to shred thin parts, but it is possible for the motor to overheat if it is used repeatedly for a long period of time. Using a hand-crank on the shredder is a potential solution to this problem, but the hand crank must be easy to turn so that it is not taking on the user.

Extruding Process:
Three designs were proposed for the extrusion process. All the proposed designs are used in industry. The proposed designs are motor driven extrusion processes, one being with an extrusion screw and the other with an auger.

A plunger extrusion design was also evaluated. The plunger method requires the part to be completely melted in order to be extruded so that large air gaps do not form within the plunger. After conducting research on the plunger extrusion method, it was found that this mostly used within micro printing and is not used in industry for larger scale extruding similar to the scope of the extrusion design needed. The different extrusion design types can be seen in Figure 1.

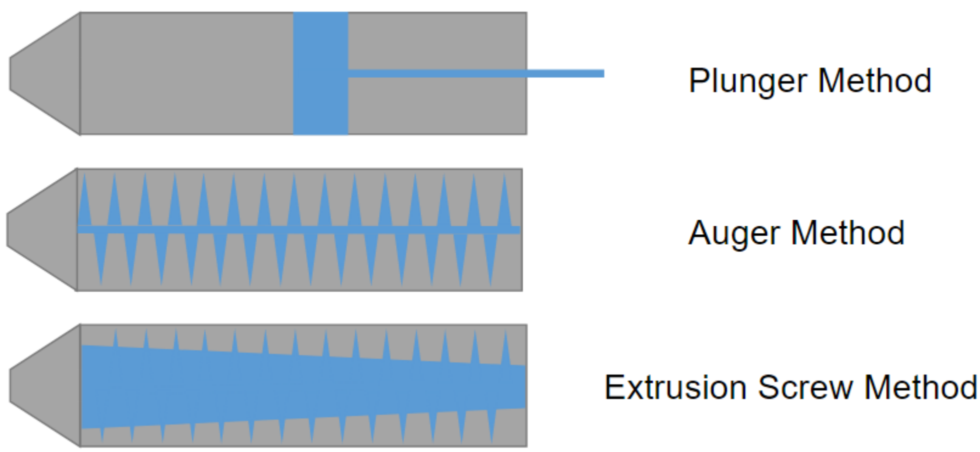

Figure 1: Extrusion Design Concepts

Spooling Process:
The gravity spool design, seen in Figure 2, was inspired by the tendency of PLA to naturally coil as it falls to a surface beneath it. Gravity spooling would require the extrusion process to be raised in order for the filament to have enough room to spool. Machine size being smaller is ideal and the gravity spooler would potentially increase the size of the overall design.

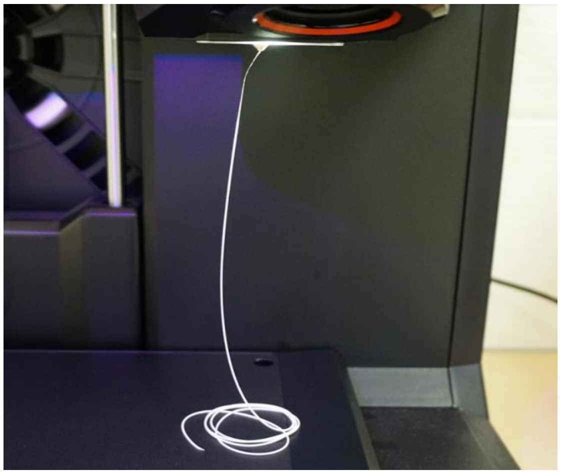

Figure 2: Gravity Spool Design

Additionally, two ways of spooling by means of a drive motor were proposed. In both cases, the motor would turn a spool through the center axis, collecting filament as it is extruded. As the filament winds up on the spool, the rate at which the spool pulls the filament increases as the diameter of the spool increases due to filling up. This must be accounted for in the design to prevent the filament from experiencing too much tension while being extruded. Too much tension becomes a problem because it runs the risk of either breaking the filament or drawing the filament to a diameter that is smaller than the desired value. Either a slip clutch or variable speed motor could solve this problem. A slip clutch would allow a specific tension to be placed on the filament, enabling the motor to turn at a constant rate.

Proposed Solution

The final design concept is a combination of all three processes described in the last section. Pugh's method was used to evaluate the proposed designs and decide upon a final design. Table 1 shows the outcomes of Pugh's method. The three main parts of the final design will be a shredder, extrusion auger, and a slip clutch for spooling

Table 1: Pugh's Method of Decision Making

Evaluation Metrics:	**Reduction Process**			**Extrusion Process**			**Spooling Process**	
	Impact	Melting	Shredding	Extrusion Screw	Auger	Plunger	Variable Speed	Slip Clutch
Cost: Less Expensive is Better	+	0	0	0	+	-	0	+
Footprint: Smaller is Better	0	0	0	0	0	-	0	0
3D Printed Part Size Capacity: Larger is Better	-	-	0	0	0	-	0	0
Less User Interactions Required is Better	-	-	0	0	0	0	0	0
Unusable PLA Filament: Less is Better	0	0	0	0	0	0	0	0
Plastic Compatibility: More Variety is Better	0	-	0	0	0	0	0	0
Weight : Lighter is Better	0	0	0	0	+	0	0	0
Total	**-1**	**-3**	**0**	**0**	**2**	**-3**	**0**	**1**

A shredder will be used for the reduction process. This will enable the user to reduce a 3D print to a consistency that is small enough for the extruder to handle. Utilizing a staging compartment for the shredded filament will help to gauge the amount of filament that has been extruded. Shredding is a potentially safer alternative to melting. Preliminary tests were completed to determine the feasibility, time to complete reduction, and risk associated to each reduction process design concept.

During the preliminary test for melting, three identical 3D parts were reduced in a controlled setting and the temperature of the part being reduced was monitored by a thermal imaging camera. The fluid PLA that was accumulating under the reducing 3D part was disturbed and the internal temperature was captured by the thermal imaging camera. It was found that a 3D part being melted has a chance of releasing strong fumes that are not encountered when shredding the material. The fumes were not created in every test but the development of fumes in one of the tests created a concern for the safety of exposing PLA to heat for long periods of time. Melting was found to be significantly slower than shredding, with the fastest of three tests completely reducing the 3D part in 15 minutes. This same part was reduced via shredding in 1.5 minutes during the preliminary shredding test. Shredding is a faster and quieter method when compared to impacting. The impact method required multiple strong to be made with a blunt object such as the hammer that was used in preliminary tests. Impacts made on the material were louder and containing the broken 3D part shrapnel after impact was difficult. The difficulty of containing the parts after impact demonstrated that the impact process would create more work for the user than shredding would. Shredding allowed for all portions of the method to be contained directly below the shredder. The noise level was compared using the "Decibel X" phone app. This device was used to compare the noise level outputs of shredding and impact to determine which is quieter. Analyzing the noise output revealed a significant difference with shredding being the quieter method. Impacting was also less efficient than shredding when reducing parts with higher infill, requiring more impacts to be made and more inconsistent sized pieces produced. As seen in Table 1, the shredder was the best option for the reduction method.

The next step in the process will be a hopper-fed extrusion process. An auger will be used in the extrusion process due to cost, and size, as seen in Table 1, and the ability to control the extrusion process. An auger would be connected directly to a motor shaft. This system, when coupled with a motor speed controller, will allow a user to quickly and easily adjust the rotational speed of the auger and effectively make fine adjustments to the output diameter of the filament. The adjustments to the motor speed will enable a user to create consistent desired results, as verified by testing the Makerbot Replicator 2 extrusion nozzle. The filament extruded at a constant motor speed from the Makerbot Replicator 2 produced a material with a consistent diameter of approximately 0.1+/- 0.01mm. The filament will pass through fixed, modified calipers with a tolerance of 0.02mm and resolution of 0.01mm. These calipers will provide a digital readout of the active diameter of the filament. A user may use the active diameter readout to determine the adjustment required for the extruder motor. Pullers will be located after the calipers to guide the filament through the calipers and to the spooler. The filament will then run through a traversing mechanism between the pullers and spooler to aid with an even disbursement of filament across the spool. The pullers, spooler, and traversing mechanism will all be connected to the same fixed-speed motor. These are connected to ensure consistent traversing across the spool and to ensure that the spool and puller do not create excess tension or slack. The spool will be rotating on an adjustable slip clutch to collect the filament in a state that a 3D printer will be able to use. An adjustable slip clutch will be used to ensure that the tension does not build between the puller and spooler as the filament being spooled changes the diameter of the spool. The slip clutch is adjustable from less than 1ft-lb to 17ft-lb of torque and will be adjusted to the appropriate setting during testing. The adjustable slip clutch was the less expensive and less time-consuming spooling option over programing a separate motor to vary speed as filament is spooled. With the reduction, extrusion, and spooling processes combined, this product will allow users to fully complete the 3D filament recycling process. Figure 3 shows the final conceptual design, highlighting the locations of each component previously mentioned.

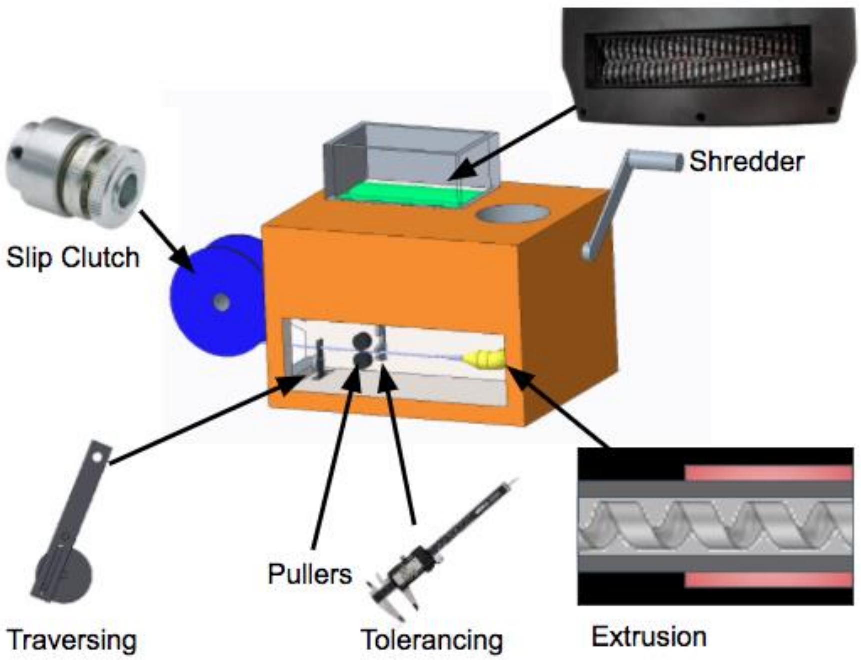

Figure 3: Final Conceptual Design

The shredder seen in Figure 3 will be a modified micro-cut paper shredder. The micro-cut shredder cuts the material into small, rectangular pieces of approximately 1/8inch^3, small enough for extrusion, as opposed to long strands that are not usable for extrusion. The paper shredder will be capable of handling parts that are contained within the safety hood above the shredder. The capacity of the shredder is estimated to be 6"x4"x4", based upon the opening of the shredder and the possible size of 3D parts printed at Ohio Northern University. The total capacity of the shredder is likely to change as product testing continues. It has been found from research that a problem with using a paper shredder is that although the rotors are capable of handling a large amount of PLA filament, the motors will eventually overheat. To combat this issue, the shredder will be modified to use a hand crank as the driving force by connecting a hand crank to the existing steel shredder frame and gear system and by removing the motor from the system. This makes it more durable and also adds a safety factor since the user will have full control over the rotation of the shredders. By having full control of the rotation of the shredder, it is less likely that an article of loose clothing may become pulled into the shredder and cause injury to the user as it continued to run.

For extrusion, an 8” long, ¾” diameter auger will be enclosed in an insulated, stainless steel pipe and turned by a 12-volt DC motor. The motor speed will be controlled by the user. Material will be fed into the auger from a hopper using gravity as the driving force of the material falling onto the auger. The pipe will be heated by one 2” long by 1” diameter heating collar, rated to achieve our desired melting temperature of ~215ºC. To ensure a proper heating temperature, a temperature controller will run the heating collar and regulate temperature using a thermocouple attached to the extruder system. The ideal location of the thermocouple used with the temperature controller will be determined through testing as the prototype is built. A 90° fitting will be threaded onto the end of the extrusion pipe. A solid hex-fitting threaded onto the opposing side of the 90º fitting will act as the nozzle. A hole of approximately 1.75mm (the desired diameter of the filament), will be drilled into the tip of the nozzle for the filament to exit. Currently, the direct competitor, Protocycler, uses this means as their nozzle. Testing will be needed to confirm the diameter of hole that best extrudes filament to the desired 1.75mm diameter. Figure 4 shows a model of the extrusion assembly.

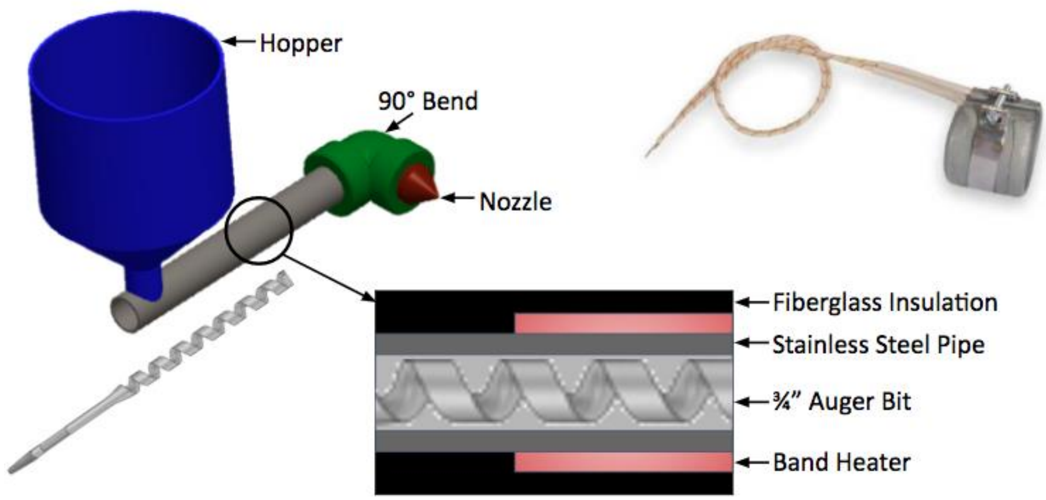

Figure 4: Extrusion Assembly

After extrusion, the filament is pulled through a traversing mechanism seen in Figure 5. The purpose of the spooling mechanism is to spread the filament evenly through the spool. The traversing pattern or width can be adjusted by changing the radius from the center of the drive wheel to the point at which the pin is fixed. This traversing mechanism allows for various sized spools to be connected to the prototype.

Figure 5: Traversing Mechanism

The filament will then be spooled by rotating an old spool at a fixed speed on a slip clutch. The slip clutch will produce a constant desired tension in the extruded filament by allowing the spool to rotate at a different speed than the speed that the motor is turning the spool. This slip occurs when a small load is applied to the spool. Utilizing the adjustable slip clutch will allow for changes to be easily made while performing the scheduled tests during the construction of the prototype.

Testing and Refinement

Shredding Process:

The first stage of testing began with the shredding process. Initially, the rafts from the 3D prints were shredded using a standard paper shredder. This testing was to ensure that the teeth on the shredder were capable of handling the load produced from the PLA. The shredder used was a cross-cut micro shredder and shredded the plastic sufficiently. Sufficient shredding was classified as having a final shredded material size of 1/8”x1/8”x1/8” based on research. The rafts used for testing are slightly thicker than a few sheets of paper, but parts that need to be shredded can be much larger and thicker than this. For parts much thicker than a raft, the shredding works best if the part is cut or smashed smaller. The shredder works for larger parts but the shredding is much more consistent with smaller input pieces. If the shredded PLA is not to the desired size, it can easily be fed through the shredder again to further reduce the size. There was concern regarding the load on the motor. While the teeth were able to shred the PLA there were concerns about the longevity of the motor since the product was designed to shred paper, which requires much less torque. To combat this issue the motor was removed, along with some of the internal gears and a hand crank was installed in place of the motor. Removal of select gears allowed for gear reduction while utilizing the existing gears within the system. The final gear ratio was reduced to approximately 6:1 so the hand crank is turned six times for each revolution of the shredding teeth. Gearing was reduced since the user is capable of producing much more torque than the original motor. This ratio was chosen because it was easily achieved using the existing gears and does not involve substantial inputs from the user, neither revolutions nor force. An added benefit of the hand crank mechanism is the system is easily reversed to clear jams or reposition the material for optimal shredding. It is also an added safety feature. The shredding teeth are very sharp and the hand crank allows for much greater control of the speed and rotation of the teeth.

Extrusion Process:

The heating band was tested two different ways. Initially, the temperature controller was used to turn the heating band on and off at a desired temperature (50°C). The following test was heating the band heater to the desired temperature of 200°C. Around 100°C, the band heater began to smoke. As the test continued, the glue holding the band heater together began leaking. This image can be seen in Figure 6. After the band heater was used multiple times the smoking stopped and functioned properly, meaning that the desired temperature was reached without any smoke or dripping from the band.

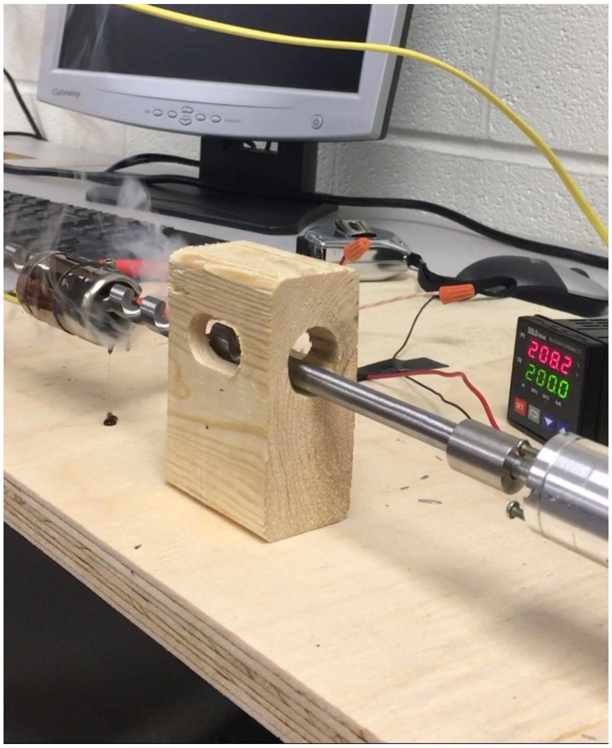

Figure 6: Band heating smoking and dripping glue at 208.2 °C

The motor that turns the extrusion auger was tested once the heating band was in working condition. The extrusion apparatus was set up and the band was heated to the desired temperature of 200°C. Then, filament was fed into the extrusion barrel through a hopper. The motor continued to turn as filament entered the barrel, pushing the filament toward the nozzle. However, the motor did not have enough torque to continue running once the barrel was completely full of filament, so there was no extrusion out of the nozzle. Figure 7 shows the end result from this test. It is an image of where the filament stopped when the motor jammed. The nozzle was removed in order to observe this.

Figure 7: Test Results from First Extrusion Attempt

The jam may have been the result of insufficient motor torque, feeding the filament in too soon before the entire extrusion system reached the desired temperature or a mixture of the two. To investigate this issue further, a new motor with a torque rating of 13 ft-lb has been purchased. Additionally, the time required for the whole system to reach the desired temperature will be measured so that the filament will only be fed into the barrel once the end of the nozzle reaches the desired temperature. If neither of these solutions solve the problem, shortening of the barrel length will be tested. Shortening the barrel length will in turn reduce the load on the motor because there will be less filament that the motor will need to push through the barrel at once.

The next step in testing the extrusion process will be to measure the diameter and tolerance. The nozzle hole diameter is currently 1.55mm. Adjusting the speed of the auger motor will change the diameter of the filament. If the desired diameter of 1.75mm cannot be reached with the 1.55mm hole, the hole size will be increased by 0.05mm. This can be repeated until the desired diameter is reached. In addition, testing will be conducted to determine if the filament meets the desired tolerance of +/- 0.05mm. This will be measured using calipers as the filament is extruded. From preliminary testing, it was found that if filament is pushed through a nozzle with a constant force, the variation in the diameter is very small and fits well within the desired tolerance.

Spooling Process:

The testing of the spooling process will start with a new spool of PLA filament and an empty spool. The spooling section of the system will be assembled and the empty spool attached. The new spool will act as the recycled filament from the extrusion process and the spooling mechanism will spool the filament from the new spool to the empty spool. Throughout this process, the motor speed and the tension of the slip clutch will be adjusted to avoid pulling filament from excess slack and avoid pulling the filament too tight, causing the extruded filament to stretch or break.

References:

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